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An investigation of road crossing in a virtual environment

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Abstract

The reported study employed a virtual reality (VR) system, using a head mounted display (HMD), to investigate road crossing behavior in children and young adults. Younger children (aged 5–9 years) made the greatest number of unsafe road crossings and the oldest participants (aged >19 years) the fewest. Overall performance was better (fewer unsafe road crossings) in uniform speed than uniform distance trials, consistent with previous research suggesting that pedestrians base road crossing decisions on inter-vehicle distance rather than vehicle speed. Results are discussed in terms of road crossing behavior and the use of VR simulations in the study of pedestrian behavior.

Keywords: Road crossing; Virtual environment; Virtual reality

1. Introduction

Pedestrian accidents are among the most common causes of death and serious injury to young children in the developed world (Ampofo-Boateng and Thomson, 1990; Connelly et al., 1996; Demetre and Gaffin, 1994; Haight and Olson, 1981; Roberts, 1995; Thomson, 1991). Recent pedestrian injuries figures from New Zealand, broken down into 5 years age groups, indicate that children aged 5–9 years accounted for the highest percentage of injuries (16%), followed by those aged 10–14 (13%) and 15–19 years (12%), with no other age group accounting for more than 7% (20–24 years). Pedestrian deaths, however, were highest for 15–19 years old (17%) and for 75–79 years old (14%) with the 5–9 and 10–14 years old age groups each accounting for only 3% of pedestrian fatalities (Land Transport Safety Authority, 2000). Similar findings are reported from the UK and US (Malek et al., 1990) and from Canada (Jonah and Engel, 1983).

The need to teach children how to judge when it is safe to cross the road is widely accepted. Effective skills training should reduce not only childhood injury but also the incidence of accidents, and especially fatalities, amongst the cohort as they age (Ampofo-Boateng and Thomson, 1990; Christoffel et al., 1986; Connelly et al., 1996; Demetre et al., 1993; Grayson, 1981; Malek et al., 1990; Yeaton and Bailey, 1978). Before effective training programs can be developed, however, children's road crossing behavior and the nature of road crossing errors need to be fully understood. Only then can educational programs targeted to reduce road crossing errors can be developed. Two major deficiencies in young children's road crossing have been identified (Thomson, 1991): the selection of appropriate locations to safely cross a road and the uptake and use of information about traffic flow which specifies whether an attempted road crossing will be successful. The present research considers only the latter, although further study of the selection of crossing locations amongst children is also advocated.

The ability to safely cross a road is a perceptual-motor skill, one that involves co-ordination between perception of the oncoming traffic and the action of walking across the road. Judgment of whether a gap in the traffic is sufficient to safely cross requires the determination of the time-to-contact of the nearest vehicle with the planned crossing line and the assessment of whether this time-to-contact exceeds the time required to cross the road, taking into account one's own locomotive speed. The task is not one of perceiving the size of the traffic gap in absolute terms but the size of the gap in terms of time to act. The size of the gap in traffic needed for safe crossing will differ between pedestrians as a function of their locomotive speed. In addition, for any given individual the size of the gap required may vary as a function of environmental (e.g. strong winds, rough road surface) and personal factors (e.g. fatigue, carrying heavy luggage). For each road crossing attempt, the pedestrian must ask themselves anew whether a gap in the traffic affords safe crossing.

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Although research consistently shows young children to be worse at making safe road crossing decisions than older children and adults (Demetre et al., 1993; Foot et al., 1999; Pitcairn and Eldmann, 2000), the visual timing skills required to make safe road crossing decisions are not beyond children even as young as 5 years of age (Lee et al., 1984; Vinjé, 1981). That is, the errors made by children in road crossing are the consequence of a failure to apply their perceptual-motor skills appropriately rather than of an inability to make the required judgments accurately.

No clear pattern of the nature of road crossing errors has emerged from the previous investigations of road crossing behavior, primarily due to the employment of different research methodologies across studies and the involvement of different age ranges of participants. Naturalistic observation is, of course, the most realistic setting for data collection (Grayson, 1975; Routledge et al., 1976; van der Molen, 1981). It does not, however, allow for experimental control of different aspects of the road crossing situation (e.g. vehicle speed) and the accurate assessment of their contribution to road crossing decision making and safety. The major difficulty with naturalistic settings is the risk of accidents associated with road crossing errors. An additional difficulty, especially for young children, is that road crossing usually occurs alongside adults. Often decisions regarding when and where to cross the road are made by adults with the children simply accompanying them (van der Molen et al., 1983). It is unclear whether young children can themselves make safe road crossing decisions if called upon to do so.

To completely remove the risk of accidents researchers have employed a number of traffic-free approaches to both measuring and teaching road crossing behavior. These techniques include chalkboard methods, videotapes (Pitcairn and Edlmann, 2000), table-top simulations (Thomson et al., 1998), and computer animations (Foot et al., 1999). Although such methods simulate many features of the road crossing situation, they require only passive involvement by participants; the participants are not required to actually cross a road. As described earlier, judgment of safe crossing gaps requires visuo-motor calibration (Lee et al., 1984), evaluating the size of gaps in the traffic relative to one's own locomotive abilities and time required to safely cross the road. Having participants make judgments about the safety of crossing the road within various gaps in the traffic without requiring them to actually cross the road does not assess this visuo-motor calibration and raises questions about the generalization of such judgments to real road crossing situations.

Some research, notably that conducted by Demetre and co–workers (1992, 1993, 1994) and Lee et al. (1984), has incorporated actual traffic into road crossing simulations, although safety is maintained as no actual road crossing occurs. Three such methods—the pretend road, the two-step task and the shout task—have been employed. The pretend road is laid out on the pavement alongside a real road, with a barrier beside the actual road. Participants stand beside and cross the pretend road to the barrier when they judge they could safely cross the adjacent real road. The advantage of this method is that the participant is active and their activity must be based on the behavior of real traffic. However, the pedestrian's viewing perspective and spatial displacement from the traffic differ when standing beside a pretend road and an actual road. These distorting characteristics may affect both the validity of measures taken and the learning acquired from such situations.

The two-step and shout tasks are conceptually similar. They involve participants standing at the roadside kerb (the shout task) or two paces back from the kerb (the two-step task). Participants are asked to indicate, by shouting or by taking two paces onto a pressure pad, respectively when they judge it is safe to cross the road. These techniques again involve real traffic and they overcome the problem of the distorted viewing perspective encountered in the pretend road task. They rely, however, on the pedestrian remembering to allow themselves time to cross the whole road rather than to complete the task at hand (shouting or taking two paces). Roadside simulations are an improvement on classroom techniques but, there is a problem with method validation, assessing whether results from the roadside simulations generalize to crossing actual roads (Demetre et al., 1993).

The present research employed a virtual reality (VR) system, using a head mounted display (HMD), in an attempt to provide participants with a realistic road crossing environment that overcomes many of the difficulties encountered by previously employed methodologies. Within the virtual environment participants can stand beside and cross a road on which virtual traffic is moving. As the participant moves, the view in the HMD changes in a manner consistent with the virtual road being a physical reality and the pedestrian actually walking across it. The visual experience of crossing the road in the virtual environment is the same as the visual experience of crossing an actual road with the same properties, within the limitations (e.g. resolution) of the VR system. Accordingly, the distorting characteristics present in road-side simulations such as the pretend road scenario are eliminated. In the virtual environment, participants are able to see when they have made a mistake and tried to cross the road when it was not safe to do so. They can make corrective action to avoid being hit (e.g. breaking into a jog or stopping) but, if appropriate, participants can be also "hit" by the virtual vehicles. The visual experience of the vehicle looming toward the moment of contact is the same as in an actual collision, but without the physical danger of such a collision. A first aim of the present research was to investigate the feasibility of using a VR system with HMD to investigate road crossing behavior.

Traffic flows, vehicle speeds and inter-vehicle distances can easily be manipulated within the virtual environment and measures of performance taken. In the present study, the speed and inter-vehicle distance of the approaching traffic were varied. In order to correctly assess whether a given gap in the traffic affords safe crossing, pedestrians must determine the time-to-contact of the approaching vehicle. Time-to-contact is a function of the speed and distance to be covered by the approaching vehicle.[1] Connelly et al. (1996, 1998) have argued that children base their road crossing decisions on distance information, failing to take into account the speed of the oncoming traffic and, hence, misjudging time-to-contact. They showed children's distance thresholds for non-safe crossing to remain constant regardless of vehicle approach speeds. Connelly et al.'s participants were a maximum of 12 years of age so it is unclear whether errors made by adults are also a function of an over-reliance on distance rather than speed information. This research also used an unusual measure of road crossing ability, having participants judge when the gap between traffic is no longer large enough for safe crossing. It is unlikely that pedestrians would normally make such a judgment, since what is important in safe road crossing is identifying whether a given gap is large enough, not the point at which it ceases to be large enough.

The present research investigated the impact of speed and inter-vehicle distance on the road crossing ability of both children and young adults in the same, realistic, experimental set-up. Vehicle speed and inter-vehicle distance were systematically varied across experimental trials to assess the extent to which pedestrians of different ages and sexes relied on speed and/or distance information in making road crossing decisions. A number of both timing and outcome measures (based on Demetre et al., 1993; for definitions see Section 2) were employed to assess road crossing behavior.

2. Method

2.1. Participants

There were 24 participants in total, 6 in each of the following age groups: 5–9, 10–14, 15–19 and >19 years. There were three females and three males in each age group. The youngest participant was 5 years old and the oldest participant 30 years old. Participants were recruited via informal social associations.

2.2. Virtual environment

The virtual environment was generated by a 800 MHz Pentium III PC with 128MB of RAM and a 32MB Riva TNT2 3D graphics accelerator card. The virtual environment was viewed through a Virtual Research Systems V8 head mounted display that contains two full-color 3.3 cm 640×480 pixel active matrix liquid crystal displays with a display rate of 60 frames/s, presenting a 48° horizontal and 60° diagonal field-of-view to each eye. The same image was presented to each eye, although the system has the potential to produce stereoscopic images. The system included a 6 d.f. head tracker (Ascension Technology Flock of Birds with extended range transmitter) with an orientation and position sample rate of approximately eight times/s.

The virtual environment consisted of a straight, flat section of road, a traffic island, a tree, sky, roadside grass, and vehicles. The road width was 6 m and was marked with continuous white edge lines and dashed central white stripes. The vehicles were modeled on a simple van that was 1.74 m in width and 4.38 m in length. All vehicles had the same dimensions but each was randomly assigned one of four colors—orange, red, yellow or white. Variation in color was included only for realism, all vehicles were easily visible and possible color effects were not investigated. The participant did not have a visible presence in the virtual environment (i.e. participants could not see themselves).

2.3. Design

The experiment was composed of a total of 14 trials. In each trial there was a flow of traffic from the right-hand side. Fig. 1 shows one frame of a typical view seen by the participant looking to their right towards the approaching traffic.

There were ten vehicles in the traffic flow and if the participant waited until all ten vehicles had passed then they could safely cross the road with no traffic in sight. The first vehicle in each trial passed by the participant within the first 1.5 s. This vehicle was included to ensure that participants would collide with a vehicle if they crossed the road immediately after the trial started without first looking for traffic. There were two different types of trial: uniform speed and uniform distance trials. In a uniform speed trial all vehicles in the traffic flow had the same speed, and in a uniform distance trial all vehicles were the same distance apart.[2] There were three levels of both uniform speed and uniform distance. In the uniform speed trials the vehicles traveled at either 40, 50 or 60 km/h.[3] In the uniform distance trials the inter-vehicle distance was either 65, 75 or 85 m. The time gap is the functionally important variable for the road crossing task and was either 4, 6, 8 or 10 s between vehicles in each type of trial. In the uniform speed trials inter-vehicle distance was varied to achieve these time gaps and in the uniform distance trials vehicle speed was varied accordingly.

[1] Perceiving time-to-contact does not depend on the independent perception of distance and speed (Schiff and Detwiler, 1979). Rather, time-to-contact under constant velocity is directly specified in a simple way in the optic array at the eye (Lee, 1976). The relative impact of speed and distance information on pedestrians is still useful information in directing the development of education programmes.

[2] In a uniform distance trial, the separation distance between any two vehicles when the first vehicle was in line with the participant was constant. The separation distance between vehicles with different velocities changes over time. The important separation, however, as far as the participant wishing to cross the road is concerned, is the separation between the vehicle that has just passed them and the next approaching vehicle.

[3] Note that the NZ speed limit for urban roads is 50 km/h.

Fig. 1. View seen by the participant from the starting position at the side of the road. The corner of the traffic island can be seen at bottom left.

The first two trials were considered training trials and data was not recorded from them. One of the training trials was a uniform speed trial and the other was a uniform distance trial. The remaining 12 trials consisted of two repetitions of the 6 trials with unique properties, 3 uniform speed trial with different speeds and 3 uniform distance trails with different distances. The order of the 12 test trials was randomly selected for each participant and within each trial, for each participant, the order of the time gaps was also randomly selected.

2.4. Procedure

Each participant was tested individually and completed two training trials and two sets of the six unique trials during an experimental session. Instructions were given verbally and the participant's questions were answered. Participants were told that their task was to cross the road to the traffic island. They were instructed that they could move around by walking and could look around by turning their head. Each trial was terminated when the participant had crossed the road to the center of the traffic island. At this point, participants were given verbal instructions to turn around and returned to the starting position, indicated by a tree in the virtual environment. There were no vehicles on the road during the return crossing. Fig. 2 shows a bird's eye view of the road crossing situation. The instructions to start the trial and to turn around were digitally recorded and automatically played through the HMD headphones. There were two experimenters present during testing; one experimenter started each trial when the participant was in the correct position, the other experimenter walked beside the participant to ensure they did not collide with any real-world objects or get tangled in the HMD cords.

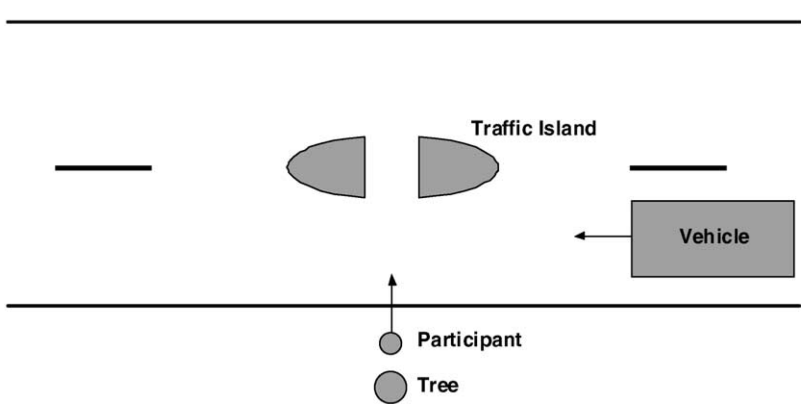

Fig. 2. A bird's eye view of the central portion of the road crossing environment. A vehicle is approaching the participant who is at the starting position by the side of the road.

2.5. Dependent measures

The recorded data were used to calculate the following measures for each participant separately for the uniform speed and the uniform distance trials.

1. *Collisions*: The proportion of road crossings in which the participant was hit by a virtual vehicle.
2. *Tight fits*: The proportion of road crossings in which the vehicle was less than 1.5 s away from colliding with the participant but did not result in collision. Although previous research (Demetre et al., 1992, 1993) has combined tight fits and collisions into a single measure, we have separated these two measures in order to get an idea of the proportion of "narrow escapes" experienced by pedestrians. These are crossings that are successfully completed but in which the vehicle passes very close to the pedestrian, including passing through the pedestrian's line of crossing, but without collision, before the crossing is completed. Tight fits are important to investigate when considering education programs for safe road crossing since pedestrians should include a margin of safety in their road crossing to account for unexpected changes in their behavior (e.g. tripping) or that of the approaching vehicle (e.g. swerving, accelerating). Defining a "narrow escape" is necessarily arbitrary. In this experiment we chose a time-gap separation between pedestrian and vehicle that matched the initial gap before the first vehicle passed the pedestrian's starting point in each experimental trial, a gap in which no participants attempted to cross the road. In addition, a gap of 1.5 s is approximately the time taken by a pedestrian to walk 1.5 m, or half the single lane of the virtual road.
3. *Cautious crossings*: The proportion of road crossings in which the participant waited until all ten cars had passed before crossing (i.e. did not cross in a vehicle gap).
4. *Crossing time*: Time gaps between vehicles as the front vehicle passed the pedestrian were either 4, 6, 8, or 10 s. The mean of the time gaps in which the participant crossed the road was calculated.
5. *Rejected gaps*: The mean of the time gaps that the participant chose *not* to cross was calculated.
6. *Number of gaps*: The mean number of gaps (and, hence, vehicles) that passed the participant prior to them crossing the road.

3. Results

Twenty-four participants each completed 12 trials giving a total of 288 trials. Each trial was classified as either a safe or an unsafe road crossing.

3.1. Incidence of unsafe road crossings

3.1.1. Collisions and tight fits

Thirteen trials (5%) resulted in collisions and 33 (12%) in tight fits. Seven participants completed their 12 experimental trials with no collisions or tight fits, although one of these seven waited on all trials for all of the cars to pass before crossing the road (cautious crossing—see subsequent sections). Of the remaining six participants who made no unsafe crossings three were aged 10–14 years (two male, one female) and three aged >19 years (two male, one female). The mean number of collisions and/or tight fits per participant for the remaining 17 participants was 2.71 (23% of trials). Of these unsafe crossings 30% were committed by children aged 5–9 years, 24% by children aged 10–14 years, 30% by children aged 15–19 years and 15% by participants aged >19 years. Males committed 39% of the unsafe crossings and females 61%. Fig. 3 illustrates the distribution of collisions and tight fits as a function of age and sex of participants.

A 2 (sex of participant: male/female) $\times$ 4 (age group: 5–9, 10–14, 15–19 and >19 years) $\times$ 2 (trial: uniform distance/uniform speed) ANOVA with repeated measures on the third factor was conducted on the number of unsafe crossings, including all participants whether or not they made any unsafe crossings. This revealed only a marginally significant

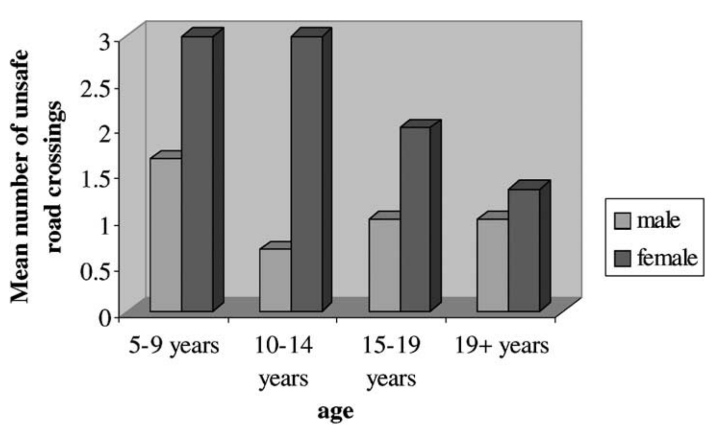

Fig. 3. Mean number of unsafe crossings as a function of age and sex.

Table 1
Mean crossing and rejected gap times (s) as a function of trial type and crossing safety

	Safe crossings		Unsafe crossings	
	Uniform speed[a]	Uniform distance[a]	Uniform speed[a]	Uniform distance[a]
Crossing gap				
Participants with no unsafe crossings	8.42 ($n = 14$)	8.30 ($n = 7$)	–	–
Participants with unsafe crossings	8.50 ($n = 9$)	8.00 ($n = 16$)	6.41 ($n = 9$)	4.81 ($n = 16$)
Rejected gap				
Participants with no unsafe crossings	5.19 ($n = 13$)	6.53 ($n = 9$)	–	–
Participants with unsafe crossings	4.50 ($n = 7$)	6.56 ($n = 13$)	6.00 ($n = 2$)	7.22 ($n = 10$)

[a] Trial type.

effect of trial type, $F(1, 16) = 3.63$, $P = 0.07$. There were more collisions and tight fits in the uniform distance than in the uniform speed trials ($M_s = 1.25$ versus 0.67). Female participants had slightly more collisions and tight fits than did male participants ($M_s = 1.17$ versus 0.75, $P = 0.30$) and the oldest participants had slightly fewer collisions and tight fits than did the three younger groups of participants ($M_s = 0.58$ versus 1.17, 0.917 and 1.17, $P = 0.28$).

3.1.2. Cautious crossings[4]

On 19 trials (7%), the participant did not cross the road until all 10 cars in the traffic flow had passed. Only four participants had one or more trial in which they waited for all 10 cars to pass before crossing the road. Of these, one female in the 5–9 age group made cautious crossings on all 12 trials and one male in the 15–19 age group made five cautious crossings. Twelve of the cautious crossings (63%) were made on uniform distance trials. Omitting the data from the participant whose crossings were all cautious increases the proportion of cautious crossings made in the uniform distance trials to 86%. However, the low total number of cautious crossings prevents any meaningful analysis of trends as a function of age, sex or trial type.

3.1.3. Timing measures

The mean duration of the gap in which participants crossed the road (*crossing gaps*) and the mean duration of gaps that they let pass before crossing (*rejected gaps*) were calculated for each participant. These time gaps were analyzed as a function of age, sex, type of trial and trial outcome (safe or unsafe).[5] Comparisons were made between those participants who made no unsafe crossings (for each trial type) and those who did make unsafe crossings. Means are shown in Table 1. Note that the number of participants varies across conditions. For the crossing gaps 23 participants made at least one safe crossing in each of the uniform speed and distance trials, nine made at least one unsafe crossing in the uniform speed trials and 16 at least one unsafe crossing in the uniform distance trials. For the rejected gaps the number of participants in each condition is reduced as some participants did not wait for any gaps between vehicles to pass before crossing the road. On 14 of the 16 unsafe crossings in the uniform speed trials (88%) and 12 of the 30 unsafe crossing in the uniform distance trials (40%) participants did not wait for a single gap before crossing.

3.1.4. Crossing gaps

As seen in Table 1, mean crossing gap times for safe road crossings did not differ as a function of trial type ($M_s = 8.46$ and 8.09 for the uniform speed and distance trials, respectively), nor as a function of whether or not participants made any unsafe road crossings ($M_s = 8.38$ and 8.18 for participants with no unsafe crossings and those with unsafe crossings). That is, all crossing gaps for safe crossings were of similar duration across trial and participant type. Crossing time for safe crossings was longer, however, than for unsafe crossings ($M_s = 8.27$ versus 5.39; $t(69) = 10.47$, $P < 0.0001$).

A 2 (sex of participant: male/female) × 4 (age group: 5–9, 10–14, 15–19 and >19 years) × 2 (trial: uniform speed/uniform distance) ANOVA, with repeated measures on the final factor and with walking speed as a co-variate, was conducted on the safe crossing gaps. This revealed a significant main effect of trial, $F(1, 15) = 5.29$, $P < 0.05$, that was qualified by a significant trial by sex interaction, $F(1, 15) = 8.95$, $P < 0.01$. Post hoc tests (Tukey, $P < 0.05$) showed the crossing gap to be larger in the uniform speed than the uniform distance trials for female

[4] Waiting until all the cars had passed before crossing the road produced a safe crossing in this experimental paradigm. Generalizing this strategy to the real-world, however, would be at best undesirable, and at worst unsafe. Trying to cross a busy road at a peak time by waiting for there to be no traffic in sight would be impractical, and may lead to frustration and the selection of inappropriate gaps. A cautious crossing strategy is not viable as the sole road crossing strategy; it is important for pedestrians to learn strategies that can be employed when traffic is present. The low number of cautious crossings suggests, however, that it is not a commonly used road crossing strategy, even in the experimental paradigm where it guaranteed safe crossing.

[5] Note that the participant who, on all trials, waited for all the cars to pass before crossing the road was excluded from these analyses.

participants ($M_s = 8.56$ versus 7.61) but not for the male participants ($M_s = 8.40$ versus 8.52).

3.1.5. Rejected gaps

As seen in Table 1, mean rejected gap times for safe road crossings differed as a function of trial type with longer mean gaps for uniform distance than uniform speed trials ($M_s = 6.55$ and 4.95; $t(40) = -3.85$, $P < 0.001$). There was no difference in mean rejected gap times for safe road crossings as a function of whether or not participants made any unsafe road crossings or not ($M_s = 5.84$ and 5.74). The rejected times were longer for the unsafe than the safe crossings ($M_s = 7.01$ versus 5.79; $t(52) = -2.31$, $P < 0.05$).

A 2 (sex of participant: male/female) × 4 (age group: 5–9, 10–14, 15–19 and >19 years) × 2 (trial: uniform speed/uniform distance) ANOVA, with repeated measures on the final factor and with walking speed as a co-variate, was conducted on the safe rejected gaps. This analysis revealed only a significant main effect of trial, $F(1, 13) = 27.99$, $P < 0.01$, with longer mean rejected gaps in the uniform distance than the uniform speed trials ($M_s = 6.55$ versus 4.95).

3.1.6. Comparing crossing and rejected gaps

For the uniform speed trials the crossing gaps were longer than the rejected gaps for safe road crossings ($M_s = 8.46$ versus 4.95; $t(41) = 11.23$, $P < 0.0001$) but there was no difference between crossing and rejected gaps for unsafe road crossings ($M_s = 6.41$ versus 6.00).

For the uniform distance trials the crossing gaps were longer than the rejected gap for safe road crossings ($M_s = 8.18$ versus 6.55; $t(43) = 4.38$, $P < 0.0001$) but for unsafe road crossings the crossing gap was shorter than the rejected gap ($M_s = 4.81$ versus 7.22; $t(24) = -3.90$, $P < 0.0001$).

3.1.7. Number of gaps

In addition to the mean length of the gaps in which participants crossed or did not cross the virtual road we also analyzed the number of gaps that participants let pass before they attempted to cross the road. The number of gaps that participants let pass is, of course, analogous to the number of cars they let pass. This analysis yielded a similar pattern of results to the length of gap analysis. For safe road crossings there was no difference in the mean number of gaps let pass by for the uniform distance and speed trials ($M_s = 0.64$ versus 0.88) but for unsafe crossing fewer gaps were let pass in the uniform speed than the uniform distance trials ($t(23) = -2.95$, $P < 0.01$; $M_s = 0.10$ versus 0.74). For the uniform speed trials more gaps were let pass on safe than unsafe crossing ($t(30) = 2.98$, $P < 0.01$; $M_s = 0.64$ versus 10) but for the uniform distance trials there was no difference in the number of gaps let pass on safe and unsafe road crossings ($M_s = 0.88$ versus 0.74).

In addition, the number of gaps let pass was used as an independent variable to assess whether the crossing gap chosen varied as a function of number of gaps that had passed. Due to the low frequency of high gap numbers, the number of gaps let pass was categorized as 0, 1 or 2 or >2. Analysis revealed an effect of gap number only in the uniform distance trials where the mean gap length was shorter the more gaps had passed prior to crossing ($M_s = 7.07$ versus 6.10 and 5.82 for 0, 1 and >2 gaps, respectively).

4. Discussion

The reported research represents a first attempt to investigate road crossing behavior using a virtual environment and a head mounted display. The results are discussed in terms of both patterns of road crossing behavior and the use of virtual reality technology.

4.1. Road crossing behavior

The results of the present research provided information about the nature of pedestrian road crossing behavior and errors. Across trials, the youngest children (5–9 years) had the highest incidence of collisions and/or tight fits in the virtual environment and the oldest participants (>19 years) the lowest incidence, as predicted. There were, however, no age-based differences on any of the timing measures suggesting that participants within this age range showed similar road crossing behavior. The over-representation of young children in road accident statistics may not be solely due to their poor road crossing skills. Although research has focused on children's road crossing behavior it is important that research also consider other groups prone to accidents. One particularly important group in this context may be the elderly. In New Zealand, 12% of pedestrian injuries and 32% of fatalities are among those aged over 65 years (Land Transport Safety Authority, 2000) and in Sweden over half the pedestrian fatalities are among those aged over 65 years (Vägverket, 1997). The ability of individuals to account for their reducing locomotive abilities as a function of aging when making road crossing judgments should be considered.

Previous research has focused on age effects in road crossing behavior but some trends in our data suggest that there may also be sex differences in road crossing behavior and the likelihood of making unsafe road crossings. Although females showed a slightly higher incidence of unsafe crossings than did males, only females showed sensitivity to trial type (uniform speed or distance) when selecting crossing gaps. Possible explanations for these differences warrant further research. First, it is possible that females react differently to the VR technology than do males which may account for their greater overall incidence of unsafe crossings. Indeed, sex differences have been reported in other simulation experiments involving time-to-contact estimations (Caird and Hancock, 1994; Manser and Hancock, 1996). Males may, however, take greater risks in road crossing than females, or use a different road crossing strategy, which could explain their lack of sensitivity to trial type. Research with children of varying ages has demonstrated a tendency toward greater injury-risk taking behavior among boys, for example amongst toddlers (Morrongiello and Dawber, 1998), 6–11 years old (Morrongiello and Rennie, 1998) and 14–18 years old (Jelalian et al., 1997). These differences have been attributed to sex-differences in cognitive-based factors such as risk appraisals and attributions (Morrongiello and Rennie, 1998), factors that could easily generalize to road crossing situations. Such differences may explain the differential sensitivity of males and females to the different types of road crossing trials in the present research.

Two types of road crossing trial were employed in the reported research—uniform speed (all vehicles in the traffic flow moved at a constant speed but with different inter-vehicle distances) and uniform distance trials (the inter-vehicle distance as the vehicles passed the pedestrian was constant but the vehicles were traveling at different speeds). The results indicate a difference in road crossing outcome and strategy across these two types of trial.

Participants performed the road crossing task better in the uniform speed trials than the uniform distance trials, consistent with research by Connelly et al. (1996, 1998). There were fewer unsafe crossings (collisions and tight fits), and fewer cautious crossings in the uniform speed than the uniform distance trials. This result suggests that people generally use distance as a guide to safe crossing gaps, and do not take full account of vehicle speed. The analysis of the crossing and rejected time gaps also suggested that a different road crossing strategy was employed in these two types of trial. In the uniform speed trials, the crossing gap was longer than the rejected gap in the safe road crossings but there was no difference between the crossing and the rejected gap in the unsafe road crossings. In addition on 14 of the 16 unsafe crossings in this condition participants crossed immediately, not waiting for any vehicles to pass before attempting to cross the road. These results suggest that errors in the uniform speed trials are a result of misjudging the amount of time available to cross safely, crossing in too short gaps without waiting for a longer, safer gap. There was no effect of the number of gaps that had passed prior to crossing in the uniform speed trials suggesting that the unsafe crossing were indeed errors of judgment rather than the consequence of frustration as the number of gaps that had to be passed up as too small increased. In the uniform distance trials the crossing gap was again larger than the rejected gap in the safe trials but in the unsafe trials the rejected gap was actually longer than the crossing gap. In addition, in only 40% of unsafe crossings in this condition did participants attempt immediate road crossings without waiting for any vehicles to pass. Longer rejected gaps may indicate poor judgment of when a gap is adequate to cross the road and, hence, missed opportunities to safely cross the road. This may then lead to frustration and risk taking with attempts to cross the road in very short gaps. Support for such an explanation comes from the analysis of the number of gaps passed prior to crossing. In the uniform distance trials the more gaps that passed prior to crossing, the shorter the gap actually chosen to cross in. This would suggest that pedestrians would accept smaller gaps after having to wait to cross.

It is important to note, however, that better performance of participants in the uniform speed than uniform distance trials does not indicate that they are unable to directly perceive time-to-collision (Lee et al., 1984; Vinjé, 1981). It may well be that participants were simply not paying attention to time-to-collision information, and that they were using some other heuristic to guide their road crossing, such as attending only to separation distance. Training programs need to educate individuals to pay attention to speed and time-to-collision information in road crossing and not to rely simply on inter-vehicle separation as a guide to safe road crossing.

The reported research involved a single straight stretch of road populated with vehicles of a single size. To gain a fuller picture of road crossing behavior and the prevalence of different types of road crossing errors, additional features (e.g. road intersections and corners, car noises, parked cars) should be added to the virtual environment. In the reported experiment pedestrians completed the road crossing task free from additional distraction. Oftentimes, however, road crossing takes place under conditions of high load from the situation (e.g. noise, other people, events in the immediate surrounding environment) and from personal distraction (e.g. thinking about other tasks). In order to investigate whether such distractions influence road crossing behavior in a systematic manner, participants should be asked to perform the road crossing task under conditions of distraction (e.g. whilst having a conversation with the experimenter, in the presence of loud machinery noise). Children often cross roads in pairs or groups and it is important to investigate peer influences on road crossing behavior.

4.2. Using virtual reality

The present research employed virtual reality technology which allowed pedestrians to cross a virtual road on which virtual traffic was moving. This technology overcomes some of the limitations of previously employed methods in examining road crossing behavior, primarily in terms of increased realism and the absence of physical danger. The relatively low cost of a VR system and the ability of the virtual environment to be manipulated make it an attractive potential tool for investigating road crossing behavior and for developing educational tools to teach children safe road crossing behavior. In order for this technology to be useful, however, it must be ensured that the virtual environment does simulate accurately actual road crossing situations and that behavior in the virtual environment is generalizable to real-world situations. Direct comparisons between VR simulations and previously employed road crossing methods (e.g. the two-step task and pretend road task) are also needed.

Anecdotal evidence from our research suggested that the environment created was an adequate simulation of a real road crossing situation. A number of participants, especially the younger ones, commented that they could not see their hands. This implies a high degree of immersion to the extent that participants were surprised by their lack of self-representation in the virtual environment. Further evidence of immersion was demonstrated by a child who appeared to be reaching out to grab bars at the traffic island. In addition, the 6-year-old girl who did not cross the road until all the cars had passed in each trial, regardless of how large a time gap there was between vehicles, had until recently attended a school in England bordered by extremely busy roads. She had been taught not to cross the road unless there was no traffic in sight, a road crossing heuristic that she generalized to the virtual environment.

It is worth noting, however, that the collision rate in this study was higher than in reality. Estimates from Sweden, for example, suggest that an individual pedestrian will have to cross a road 500,000 times before they are involved in a collision whereas in the present research there was a collision approximately every 22 road crossings. The high collision rate in this research may be a consequence of the novel VR environment (see subsequent sections) or may reflect greater risk taking behavior in the safe virtual environment. The greater incidence of collisions, and related unsafe road crossings, may however be advantageous for education programs using simulation training as more opportunities for learning from one's errors (without physical danger) are provided than in real road crossing.

The present research indicates that VR can successfully be used in the study of road crossing behavior. There are also, however, some limitations and drawbacks inherent in using virtual reality equipment. Some of these limitations can be addressed with design improvements and further software development, while others will likely be lessened in the future with the continued evolution of virtual reality technology.

The HMD itself may limit the effectiveness of the simulation of a real-world road crossing situation. The weight of the HMD and restrictive nature of the cables leads to greater difficulty in looking and moving around the virtual environment than is normally experienced in the real-world. It is possible, therefore, that participants who make unsafe road crossings in the virtual environment do so because they are basing their judgements on when it is safe to cross on their *normal* walking speed, not fully taking into account the hindrance of the HMD. This may explain the higher than expected incidence of unsafe crossings in this study. However, the pedestrian should be able to adapt to a slower walking speed; wearing the HMD could be considered analogous to crossing the road when carrying large or heavy items or perhaps suffering from a restrictive injury. More importantly, the HMD has a horizontal field-of-view of 48° whereas normal human vision has a horizontal field-of-view of 180°. This reduction in horizontal field-of-view has the effect of limiting peripheral vision and the ability to walk in one direction while looking in another. In the virtual environment participants tended to look towards the traffic island in order to know which direction they were walking. It is unclear whether participants in real-world settings look back towards the traffic during road crossing, hence, acquiring more information about approaching traffic, than is possible in the virtual environment. As HMDs become more sophisticated and lightweight such restrictions will likely reduce and the simulation of real road crossing will become more realistic still. These restrictions imposed by the HMD are unlikely to have differentially affected behavior on the two types of experimental trial (uniform speed and uniform distance) and so, while offering a possible explanation for the high rate of unsafe crossings, cannot explain the pattern of unsafe crossings across trial type.

The VR system used in this research has the potential to produce stereoscopic images but in the reported research, due to technical difficulties, the same image was presented to each eye. This type of imagery (synoptic images) has been shown to reduce the perceived depth in an observed scene (Koenderink et al., 1994, 1995), hence, reducing perceivers' ability to accurately perceive the distance of the approaching vehicles. Although the use of synoptic images reduces the accuracy of the simulation in the present study, there were still a number of cues to distance available to perceivers—perspective, relative size, height in the field-of-view and motion parallax.

Future research should, however, employ stereoscopic images and also increase the update rate of the tracking system. Additional cues such as sound should also be added to future simulations. The sound of approaching vehicles may provide additional useful information to pedestrians regarding time-to-collision. Inclusion of sound effects must use an accurate algorithm, including appropriate variations in pitch, volume and 3D localization. If the sound generation method used is not accurate, then information available to the participant from the modalities of sight and hearing will be in conflict.

The present research investigated the road crossing behavior of children and young adults using a virtual reality system and head mounted display. Results indicated that younger children tended to have more collisions and/or tight fits than older children, although there were no age effects on any of the timing measures employed. Overall pedestrians performed better (fewer unsafe road crossings) in uniform speed than uniform distance trials, suggesting that pedestrians may base their road crossing behavior primarily on inter-vehicle distance. Future research employing virtual reality technology in this domain is advocated.

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References

Ampofo-Boateng, K., Thomson, J.A., 1990. Child pedestrian accidents: a case for preventive medicine. Health Educ. Res. 5, 265–274.

Caird, J.K., Hancock, P.A., 1994. The perception of arrival time for different oncoming vehicles at an intersection. Ecol. Psychol. 6, 83–109.

Christoffel, K.K., Schofer, J.L., Jovanis, P.P., Brandt, B., White, B., Tanz, R., 1986. Childhood pedestrian injury: a pilot study concerning etiology. Accid. Anal. Prev. 18, 25–35.

Connelly, M.J., Isler, R., Parsonson, B.S., 1996. Child pedestrian's judgements of safe crossing gaps at three different vehicle approach speeds: a preliminary study. Educ. Treatment Children 19, 19–29.

Connelly, M.J., Conaglan, H.M., Parsonson, B.S., Isler, R.B., 1998. Child pedestrians' crossing gap thresholds. Accid. Anal. Prev. 30, 443–453.

Demetre, J.D., Gaffin, S., 1994. The salience of occluding vehicles to child pedestrians. Brit. J. Educ. Psychol. 64, 243–251.

Demetre, J.D., Lee, D.N., Pitcairn, T.K., Grieve, R., Thomson, J.A., Ampofo-Boateng, K., 1992. Errors in young children's decisions about traffic gaps: experiments with roadside simulations. Brit. J. Psychol. 83, 189–202.

Demetre, J.D., Lee, D.N., Grieve, R., Pitcairn, T.K., Ampofo-Boateng, K., Thomson, J.A., 1993. Young children's learning on road crossing simulations. Brit. J. Educ. Psychol. 63, 349–359.

Foot, H., Tolmie, A., Thomson, J., McLaren, B., Whelan, K., 1999. Recognizing the hazards. Psychologist 12, 400–402.

Grayson, G.B., 1975. Observation of pedestrian behavior at four sites. TRRL Rep. 670.

Grayson, G.B., 1981. The identification of training objectives: what shall we tell the children? Accid. Anal. Prev. 13, 169–173.

Haight, F., Olson, R.A., 1981. Pedestrian safety in the United States: some recent trends. Accid. Anal. Prev. 13, 43–55.

Jonah, B.A., Engel, G.R., 1983. Measuring the relative risk of pedestrian accidents. Accid. Anal. Prev. 15, 193–206.

Koenderink, J.J., van Doorn, A.L., Kappers, M.L., 1994. On so-called paradoxical monocular stereoscopy. Perception 23, 583–594.

Koenderink, J.J., van Doorn, A.L., Kappers, M.L., 1995. Depth relief. Perception 24, 115–126.

Land Transport Safety Authority, 2000. Motor accidents in New Zealand: Statistical Statement Calendar Year 2000. Wellington, New Zealand.

Lee, D.N., 1976. A theory of visual control of braking based on information about time-to-collision. Perception 5, 437–459.

Lee, D.N., Young, D.S., McLaughlin, C.M., 1984. A roadside simulation of road crossing for children. Ergonomics 27, 1271–1281.

Manser, M.P., Hancock, P.A., 1996. Influence of approach angle on estimates of time-to-contact. Ecol. Psychol. 8, 71–99.

Malek, M., Guyer, B., Lescohier, I., 1990. The epidemiology and prevention of child pedestrian injury. Accid. Anal. Prev. 22, 301–313.

Pitcairn, T.K., Eldmann, T., 2000. Individual differences in road crossing ability in young children and adults. Brit. J. Psychol. 91, 391–410.

Roberts, I., 1995. What does a decline in child pedestrian injury rates mean? Am. J. Public Health 85, 268.

Routledge, D.A., Repetto-Wright, R., Howarth, C.I., 1976. The exposure of young children to accident risk as pedestrians. Ergonomics 17, 457–480.

Schiff, W., Detwiler, M.L., 1979. Information used in judging impending collision. Perception 8, 647–658.

Thomson, J.A., 1991. The Facts About Child Pedestrian Accidents. Cassell, London.

Thomson, J.A., Ampofo-Boateng, K., Lee, D.N., Grieve, R., Pitcairn, T.K., Demetre, J.D., 1998. The effectiveness of parents in promoting the development of road crossing skills in young children. Brit. J. Educ. Psychol. 68, 475–491.

Vägverket, 1997. Swedish National Road Association.

van der Molen, H.H., 1981. Pedestrian Ethology. Doctoral dissertation, University of Groningen, The Netherlands.

van der Molen, H.H., Kerkhof, J.H., Jong, S.A., 1983. Training observers to follow children and score their road crossing behaviour. Ergonomics 26, 535–553.

Vinjé, M.P., 1981. Children as pedestrians: abilities and limitations. Accid. Anal. Prev. 13, 225–240.

Yeaton, W.H., Bailey, J.S., 1978. Teaching pedestrian safety skills to young children: an analysis and 1 year follow-up. J. Appl. Behav. Anal. 11, 315–329.